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The major accomplishments during this period are summarized in the enclosed abstract which was submitted to the AIAA Aerospace Sciences meeting. Good progress is being made in both supersonic combustion and transition simulation.

NUMERICAL MODELING OF TURBULENT SUPERSONIC REACTING COAXIAL JETS *

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Abstract

An ongoing research effort is underway to investigate the physical phenomena within supersonic flows that sustain chemical reactions. An earlier study to develop accurate physical models for supersonic reacting flowfields focused on two-dimensional laminar shear layers. The objective of this work is to examine the mixing and subsequent combustion within turbulent reacting shear layers.

To conduct this study, a computer program has been written to solve the axi-symmetric Reynolds averaged Navier-Stokes equations. The numerical method uses a cell-centered finite volume approach and a Runge Kutta time-

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stepping scheme. The Reynolds averaged equations are closed using the eddy viscosity concept. Several zero-equation models have been tested by making calculations for a H_2 - air non-reacting coaxial jet flow. Comparisons made with experimental data indicate that Cohen's eddy viscosity model provides best agreement. The finite rate chemistry model used in the study of two-dimensional laminar shear layers is being incorporated into the computer program and data is being compared from a recent experiment performed at NASA Langley.

Introduction

Research is currently underway to develop advanced propulsion systems capable of sustaining hypersonic flight within the atmosphere. Included in this effort is a program at the NASA Langley Research Center to develop a hydrogen fueled supersonic combustion ramjet or scramjet engine. The success of this endeavor requires the capability to numerically predict the complex flowfields within scramjet engines.

The flowfield within a scramjet combustor is characterized by the interaction of several physical processes including turbulent fuel-air mixing and kinetically controlled combustion. Two coaxial streams mixing and burning within a free shear layer simulates the parallel injection of hydrogen fuel in a scramjet combustor. This flowfield does not possess the complexities arising from the geometry of a scramjet combustor but retains the fundamental problem of turbulent mixing and its effect upon chemical reactions. A quantitative examination of the turbulent combustion of coaxial streams is the focus of a present experimental effort at NASA to provide a test of present numerical modeling capabilities.

Combustion within a supersonic stream is marked by short residence times. Hence, assuming complete or equilibrated combustion is often inaccurate. The finite rates of reaction are accounted for by including within the fluid equation set a species conservation equation providing for the production or loss of each species. Thus, the Navier-Stokes equations augmented with appropriate species conservation equations are the governing equations for supersonic reacting flowfields.

The present work is an extension of the work of Drummond et al [1] to coaxial reacting jets. The numerical method adopted for this study integrates the Reynolds averaged Navier-Stokes equations using a finite volume

approach while advancing the solution forward in time using a Runge-Kutta scheme. The chemical source terms are treated in a point implicit manner to alleviate the stiffness in the equation set arising from the disparate time scales within the flowfield [2].

The first phase of this work consisted of determining the ability of a number of eddy viscosity models in modeling the turbulent mixing of non-reacting supersonic coaxial H_2 - air jets [3]. The aim of this phase is to eliminate those models that are unable to predict the experimental measurement from further consideration. The models selected were those of Eggers [3], Cohen [4], and Baldwin-Lomax [5]. Following is a brief description of the turbulence models and the results obtained from applying these models to coaxial jet flow. Based on these results Eggers' and Cohen's eddy viscosity models are being used in the study of reacting H_2 - air reacting jets.

Turbulence Models

Eddy viscosity models for jet flow take the general form, first proposed for incompressible flow by Prandtl,

$$\mu_t = k\rho V L \tag{1}$$

where k is an empirically determined constant, V is a characteristic velocity scale and L is the width of the mixing layer. The models differ primarily in how the characteristic scales are evaluated.

Eggers' z-difference model is defined as

$$\mu_t = k(\rho u)_o z \tag{2}$$

where $(\rho u)_o$ is the mass flux per unit area on the jet center line and z is the width of the mixing layer. This width is defined as the radial distance between the points in the profile where the local velocities are u_1 and u_2 as given by the following equations:

$$u_1 = u_a + .95(u_o - u_a) \tag{3}$$

$$u_2 = u_a + .5(u_o - u_a) \tag{4}$$

where u_o and u_a are the velocities at the centerline of the inner jet and in the external flow of the outer jet, respectively.

Eggers' kinematic z-difference model incorporates radial variation in the model by using the local density in its definition of the eddy viscosity coefficient, i.e.

$$\mu_t = k\rho u_o z \tag{5}$$

Cohen modified Prandtl's model to formally account for density variations across the mixing layer and to account for the turbulence initially present in the jets. His model is then defined by the following equations

$$\mu_t = k\rho u_o(1-m)(f\frac{1+n}{2})^{.8} \tag{6}$$

$$\mu_t = k\rho u_o(1-m_1)(\frac{1+n_1}{2})^{.8}(\frac{1+n_1}{1+n})(\frac{1+mn}{1+m_1 n_1}) \tag{7}$$

where m is the velocity ratio u_a/u_o, n is the density ratio ρ_a/ρ_o, f is an additional empirical constant, and m_1 is a velocity ratio fixed by the turbulence level which as in Ref. 3. was set equal to .4 . The value of n_1 is calculated at the axial location where $m = m_1$. Finally, Equation (6) is to be used if $m \leq m_1$ and Equation (7) for $m > m_1$.

The Baldwin-Lomax model for the outer region of turbulent wall boundary layers was designed to be used in wakes as well. It is defined as

$$\mu_t = k\rho F_{Wake} F_{Kleb}(y) \tag{8}$$

where F_{Wake} is defined as the smaller of the following two expressions

$$F_{Wake} = y_{max} F_{max} \tag{9}$$

$$F_{Wake} = C_{wk} y_{max} u_{diff}^2 / F_{max} \tag{10}$$

$F_{Kleb}(y)$ is the Klebanoff intermittency factor, u_{dif} is the difference between the maximum and minimum total velocities in the profile, and C_{wk} is an additional empirical constant. The function F is defined as

$$F(y) = y|\omega| \tag{11}$$

where ω is the vorticity. The quantity F_{max} is the maximum value of $F(y)$ that occurs in a profile and y_{max} is the value of y at which it occurs. Hence, the distribution of vorticity is used to determine the length scale.

Results

The schematic of the coaxial flow experiment conducted by Eggers [3] is shown in Figure 1. In this experiment a jet of hydrogen is exhausted into a co-flowing jet of air. The diameters of the inner and outer nozzles are 1.16 cm and 15.2 cm, respectively. The Mach number, Reynolds number per meter, velocity, pressure, and total temperature are .9, 1.2×10^7, 1100 m/s, 1 atm., and 300 K, respectively, at the exit of the hydrogen jet and 2.5, 1.4×10^8, 600 m/s, 1 atm., and 300 K, respectively, at the exit of the outer jet. The computational grid used for the following calculations is 41 x 99 with grid stretching at the interface between the coaxial jets. The thickness of the lip was not accounted for in the calculations. The grid extended twenty inner diameters in the flow direction and three inner diameters in the transverse direction.

The integration was continued until the L2 norm of the residual taken over the entire solution domain dropped four orders of magnitude which typically required 7000 iterations.

In the first calculation, Eggers' z-difference eddy viscosity model is used with three different values for the leading constant. The centerline distribution of velocity and hydrogen mass fraction are shown in Figures 2-3. The increase in velocity near the beginning of the solution domain is due to a pressure pulse generated at the interface of the two jets. This pulse whose magnitude is approximately 8 % of the static pressure propagates along the inflow boundary of the inner pipe. The inner jet subsequently expands raising the velocity. Comparison of the hydrogen mass fraction along the centerline in Figure 3 reveals the models inability to predict the extent of mixing at the last two axial locations without greatly overpredicting the mixing at the first two axial locations.

Eggers' kinematic z-difference eddy viscosity model provides a much improved prediction of the mixing as shown in Figures 4-5. The leading constant was taken to be .0164, while the turbulent Prandtl number and turbulent Lewis number were both set equal to 1.

Comparison of the results obtained from Cohen's eddy viscosity model and Eggers' kinematic z-difference eddy viscosity model are shown in Figures 6-16. The leading constant for Cohen's model was .024 where the definition of the width of the mixing layer was the same as the definition used in Eggers' model. The turbulent Prandtl number and turbulent Lewis number were also both set equal to 1. Figures 6-7 show the centerline distributions of velocity and hydrogen mass fraction, respectively. Figure 8 shows the

initial velocity profiles while the computed velocity profiles at four axial locations are shown in Figures 9-12. Also, the computed hydrogen profiles at four axial locations are shown in Figures 13-16. Both models provide a good prediction of the extent of mixing within the shear layer. Cohen's model appears to provide slightly better agreement with experimental data, although results from Egger's model may improve with a turbulent Prandtl number less than one.

Finally, predictions from the Baldwin-Lomax model are shown in Figures 17-18. The vorticity is very large within the initial profile. Hence, the eddy viscosity coefficient calculated by the Baldwin-Lomax model was small in the early portion of the solution, and consequently, the mixing is greatly underpredicted. This problem was remedied by effectively limiting the calculated value of the vorticity. Results from this modified Baldwin-Lomax model are also shown in Figures 17-18. The plot of the centerline distribution of the hydrogen mass fraction indicates that even when sufficient mixing is predicted initially, the extent of the mixing is still underpredicted at the last two axial locations. Consequently, the Baldwin-Lomax model is deemed unsatisfactory for predicting turbulent coaxial jet flow.

We are in the process of incorporating the chemistry model of Ref. 1 into the computer code. Comparisons will be made with recent measurements being carried out at the NASA Langley Research Center. Earlier measurements and calculations were reported by Chitsomboon et al [6] .

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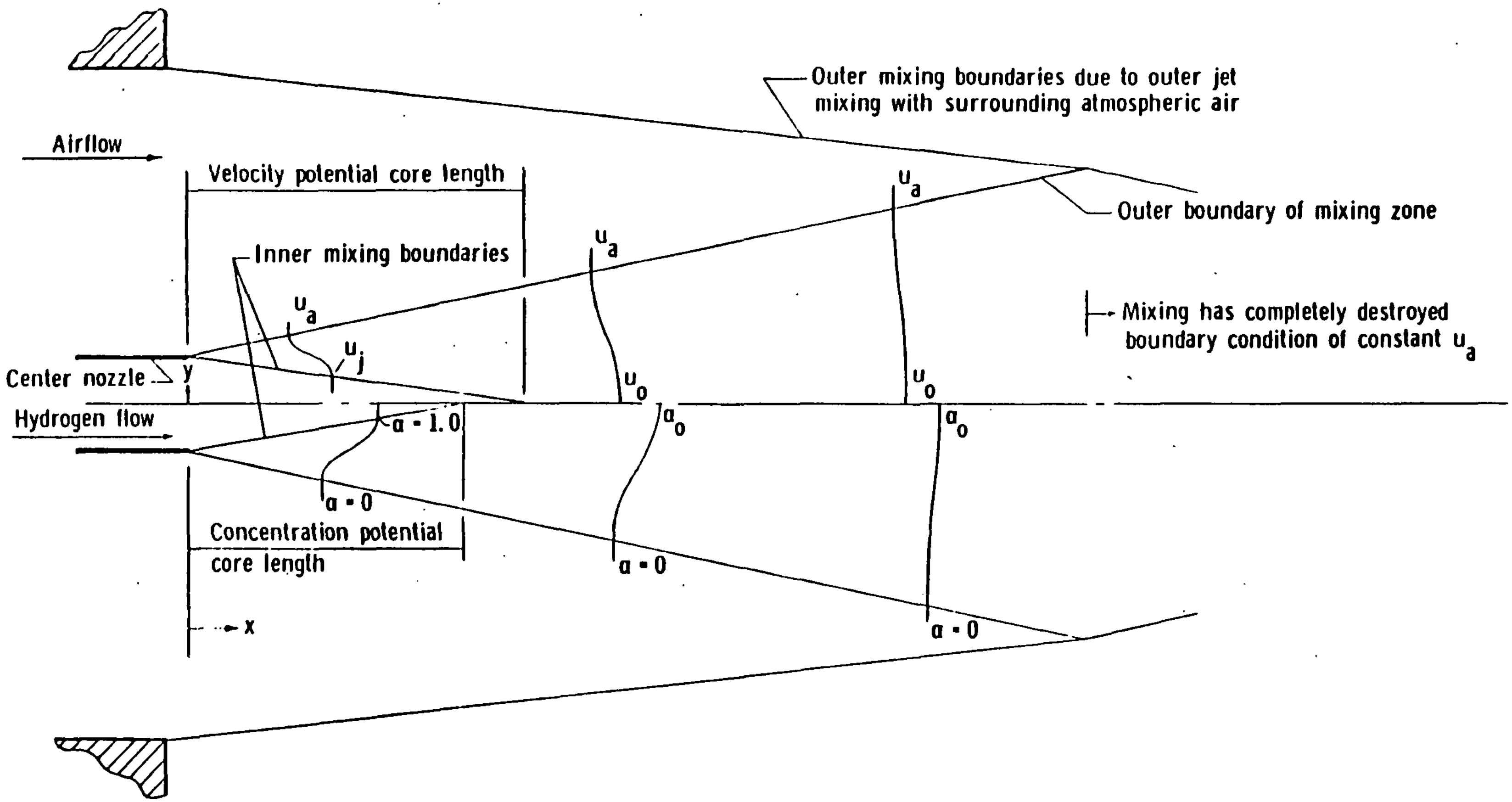

Fig. 1 Schematic of the Coaxial Flowfield

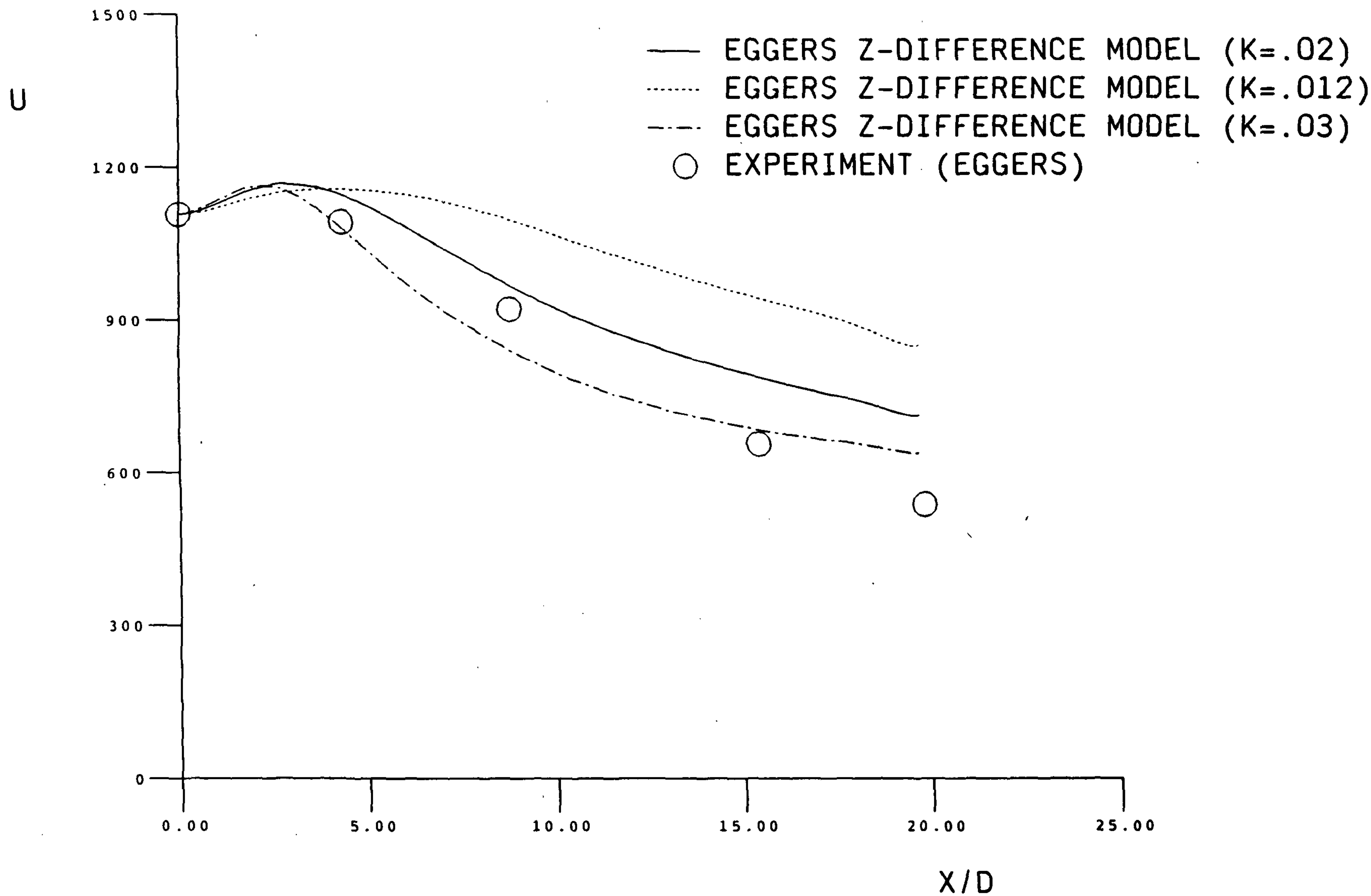

Fig. 2 Velocity Distribution Along the Centerline

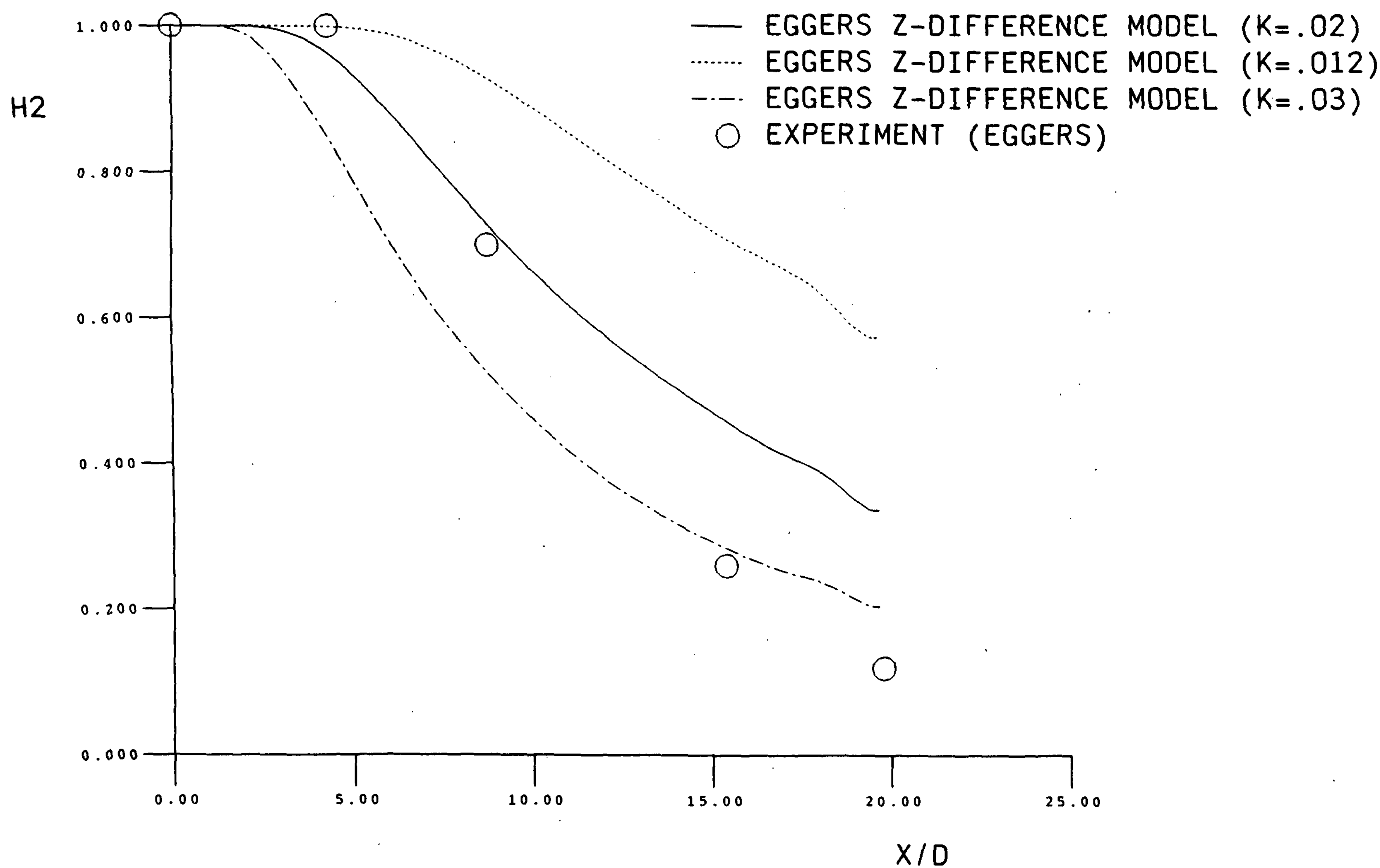

Fig. 3 Hydrogen Mass Fraction Distribution Along the Centerline

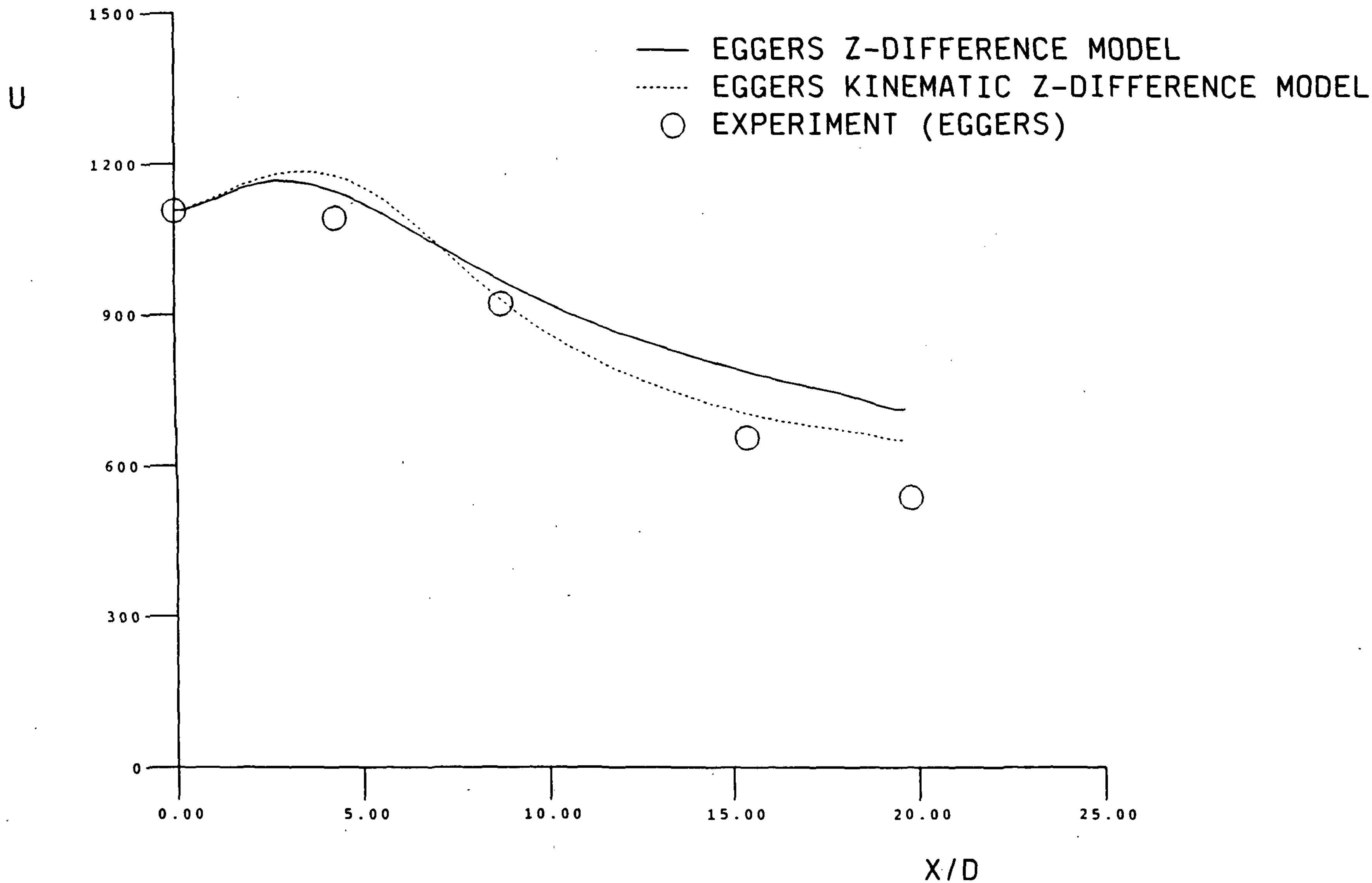

Fig. 4 Velocity Distribution Along the Centerline

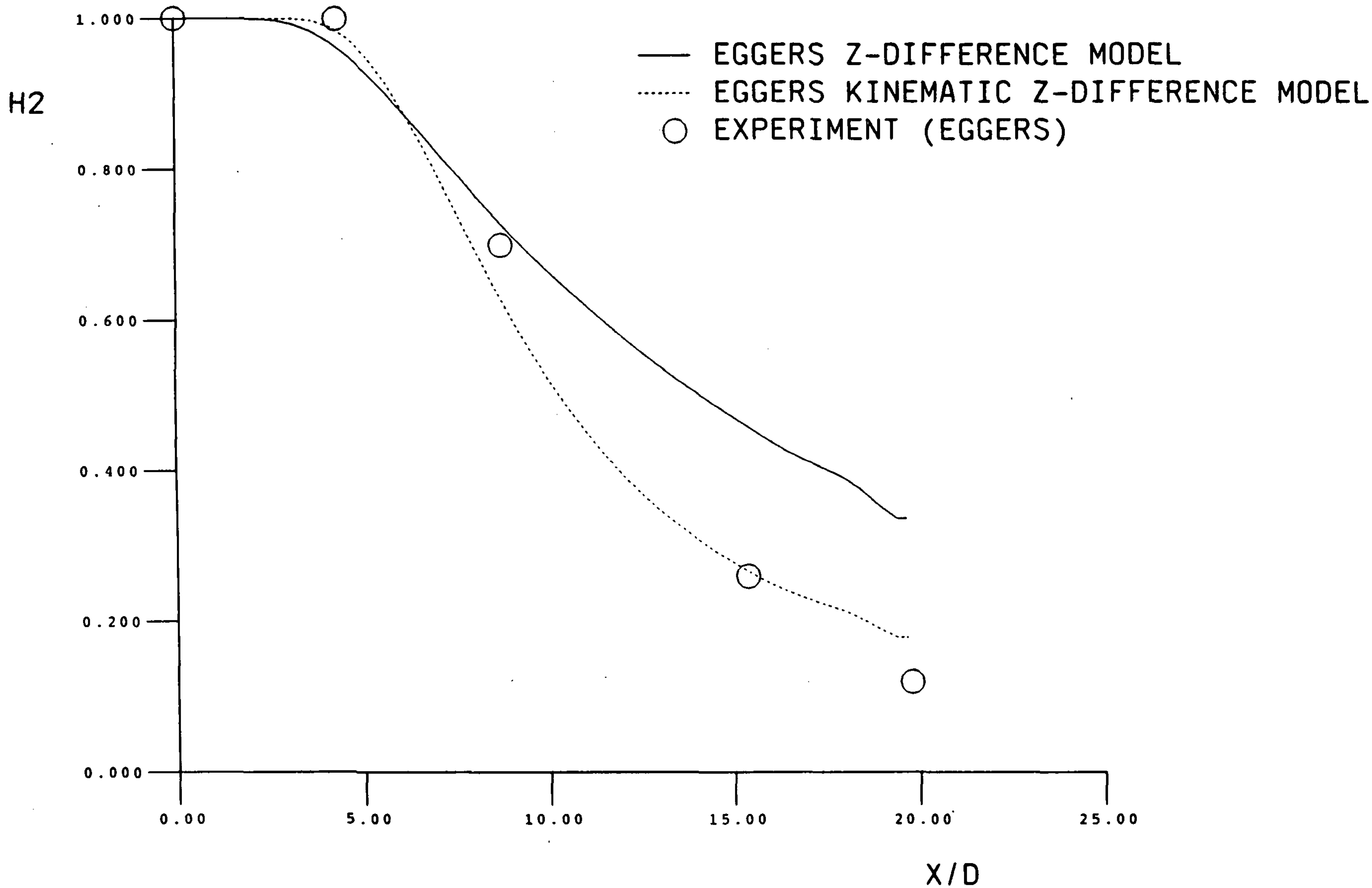

Fig. 5 Hydrogen Mass Fraction Distribution Along the Centerline

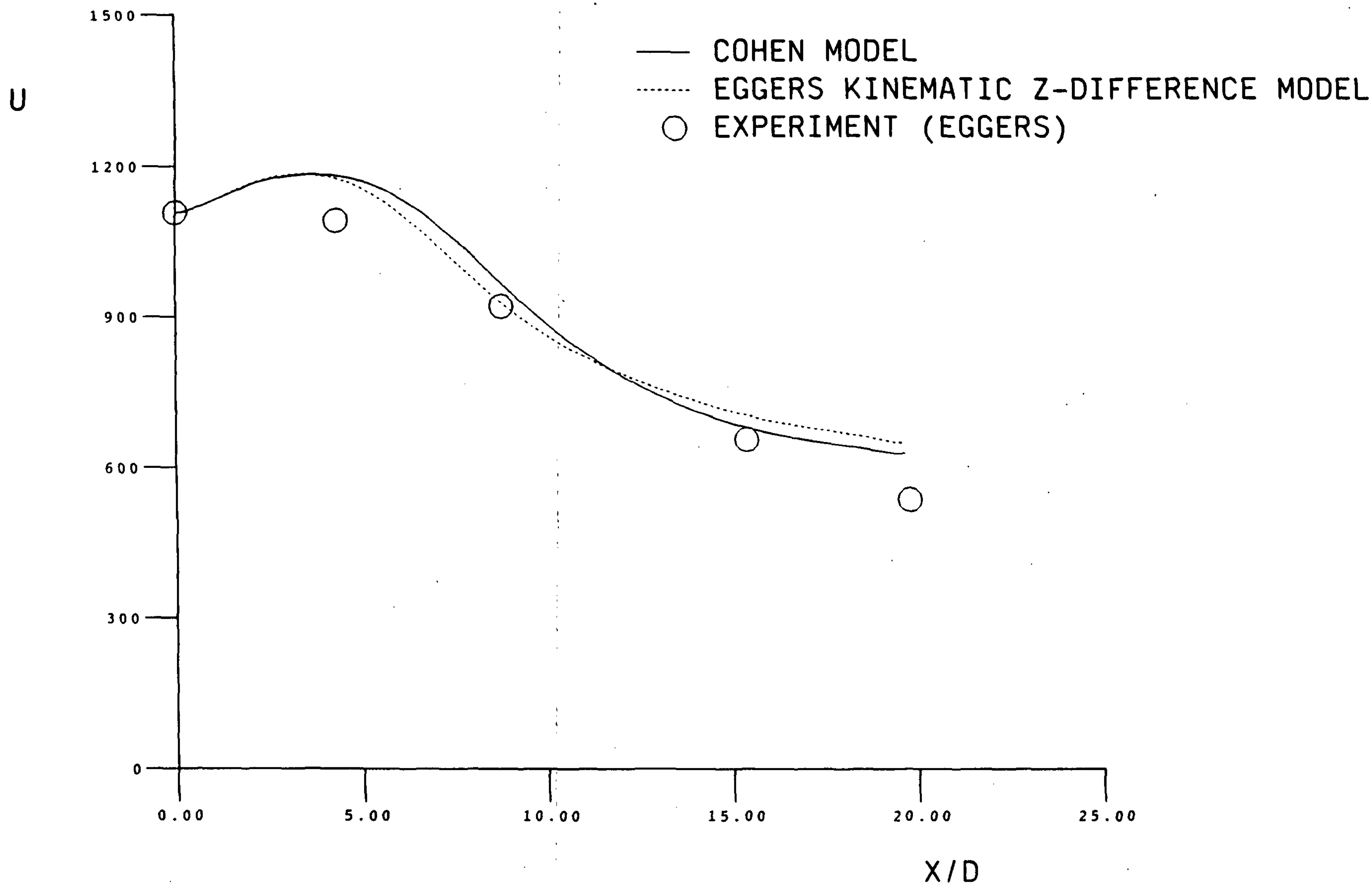

Fig. 6 Velocity Distribution Along the Centerline

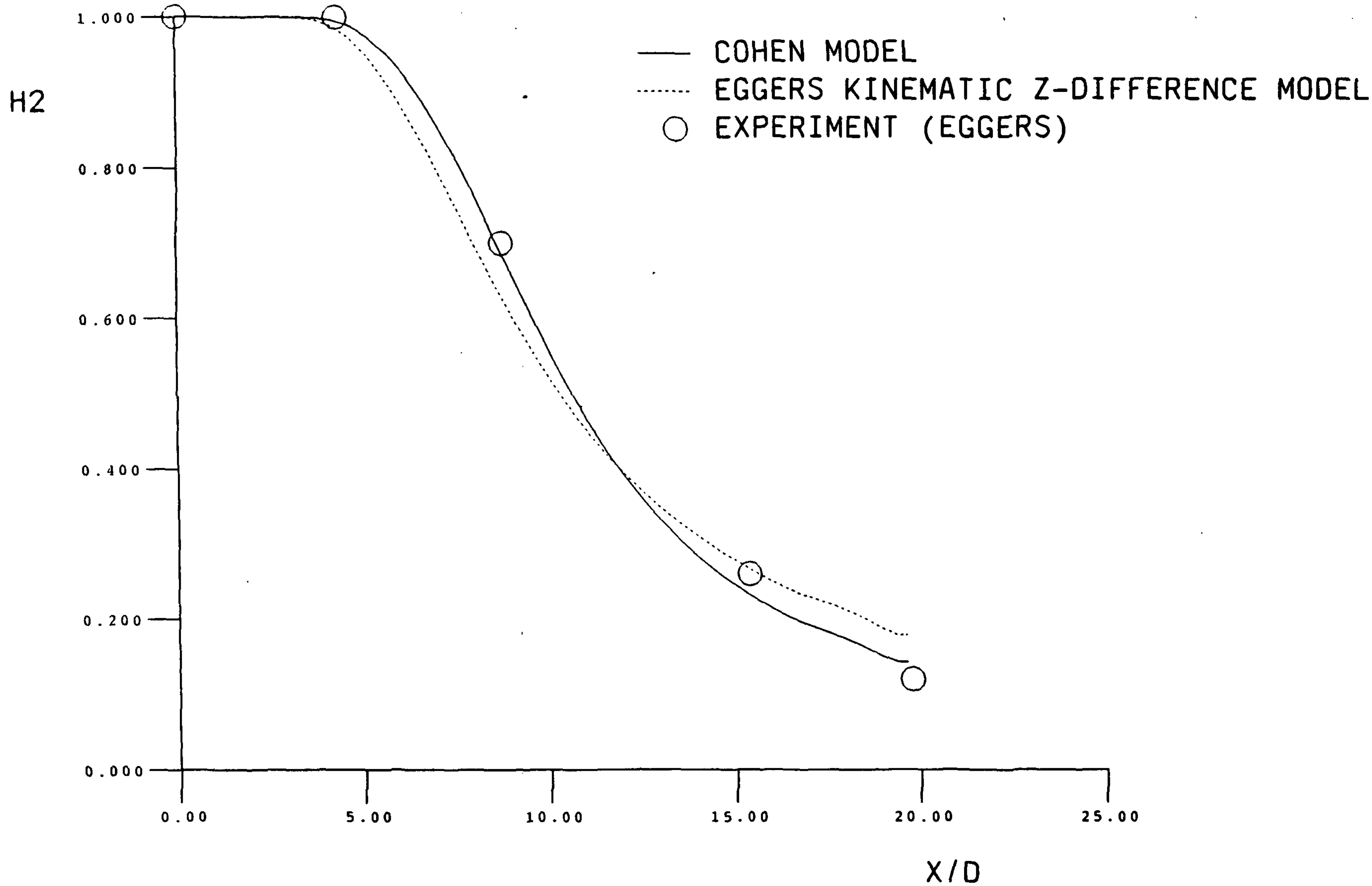

Fig. 7 Hydrogen Mass Fraction Distribution Along the Centerline

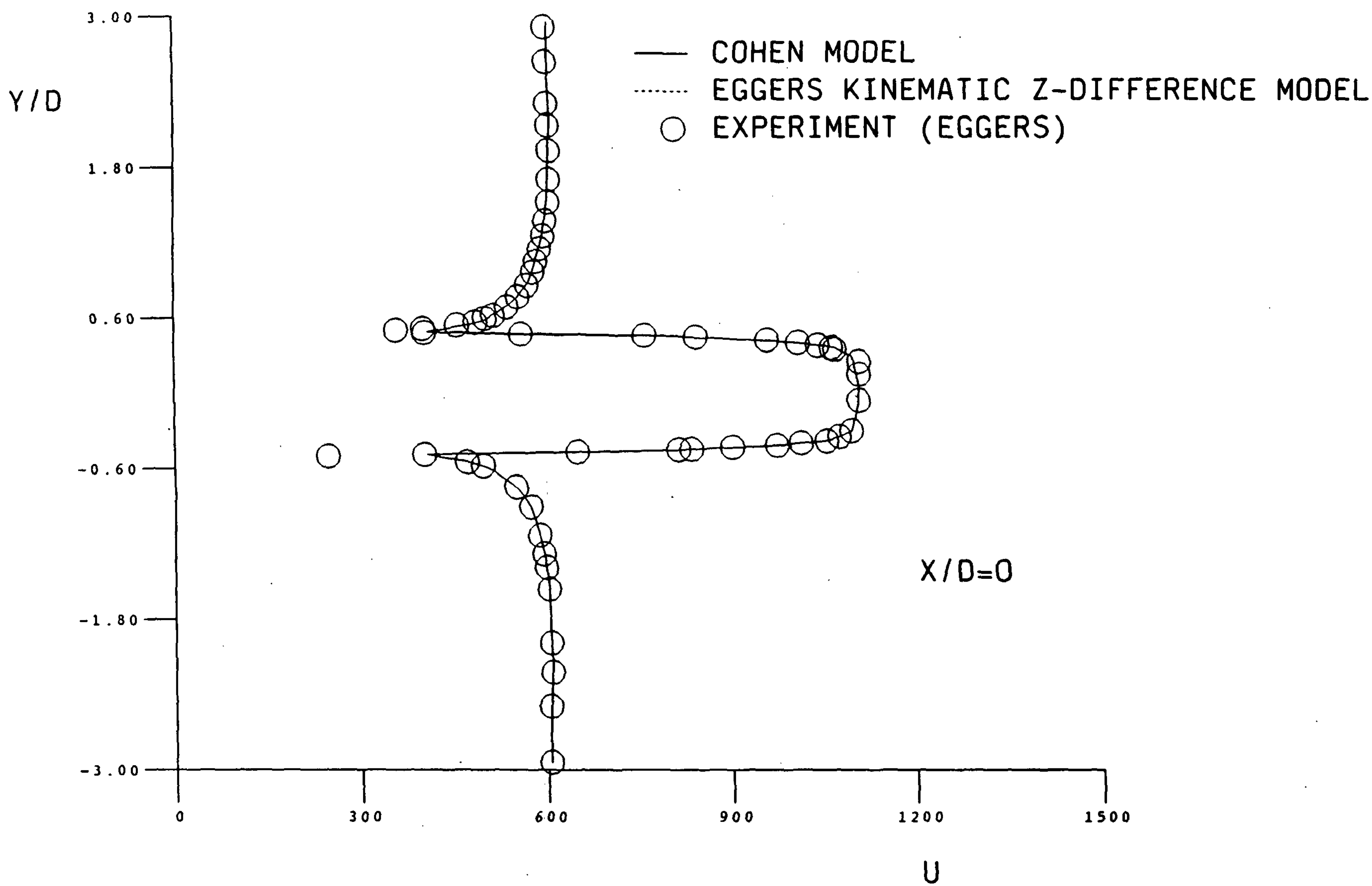

Fig. 8 Velocity Profile

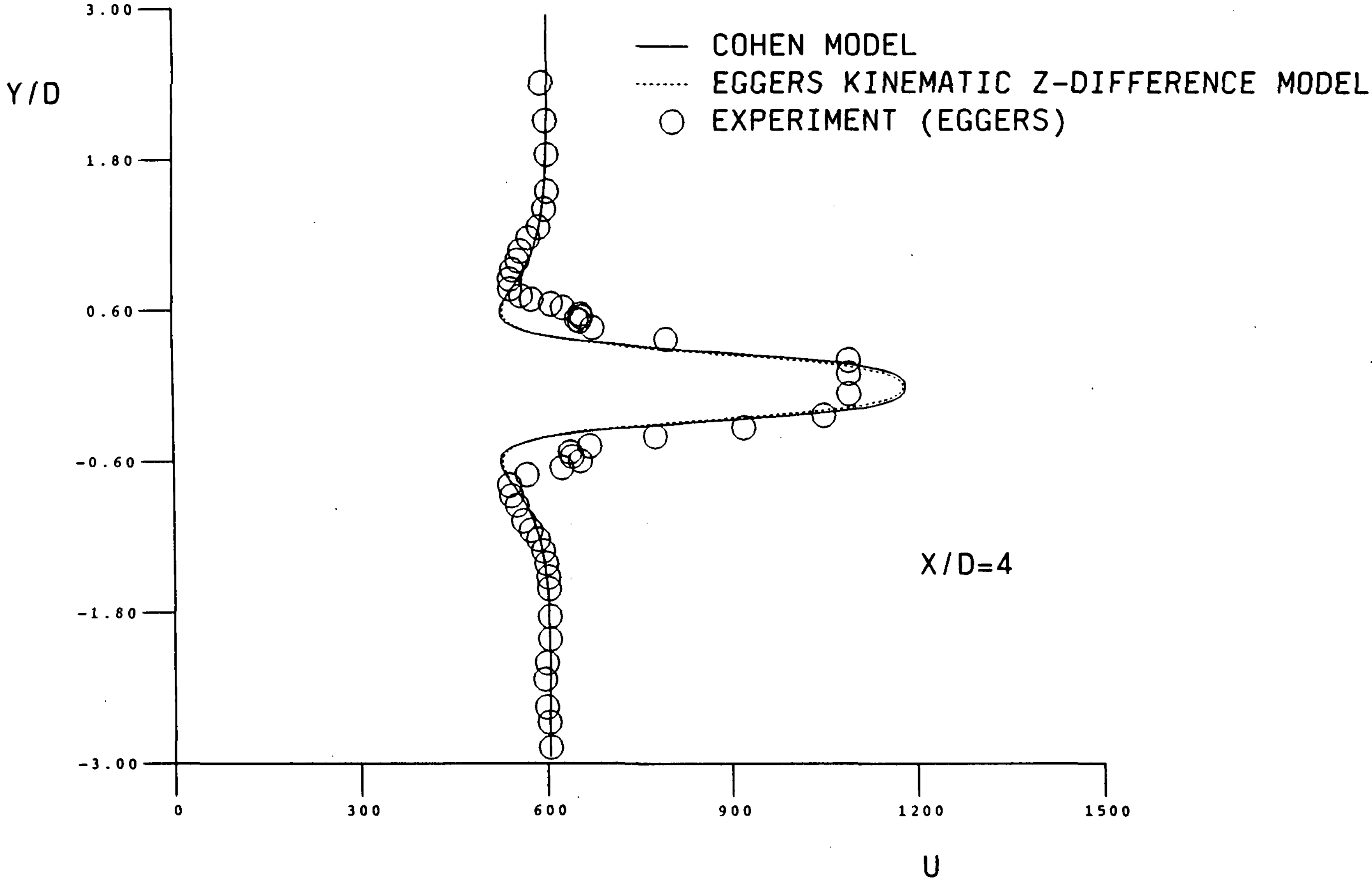

Fig. 9 Velocity Profile

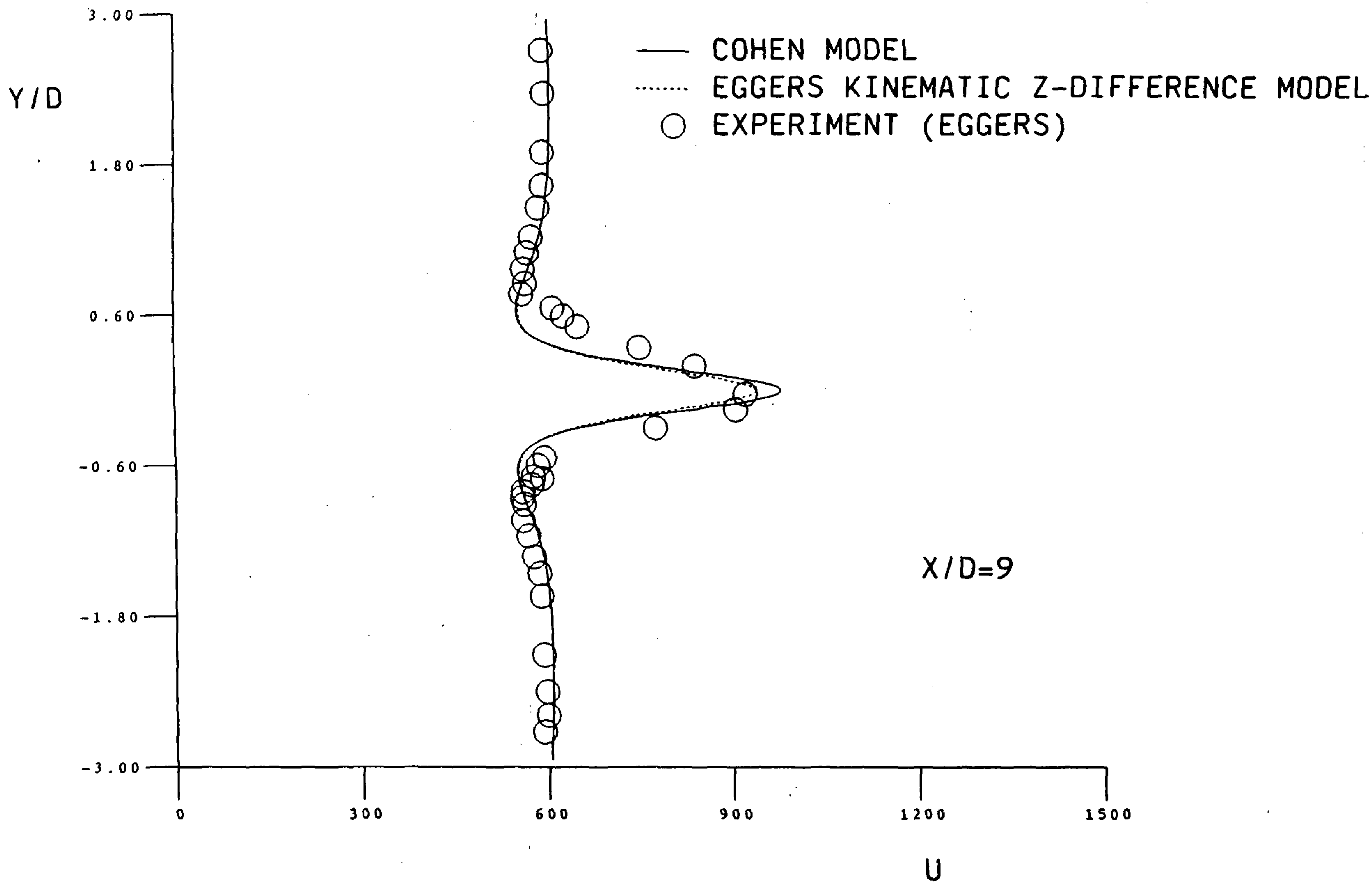

Fig. 10 Velocity Profile

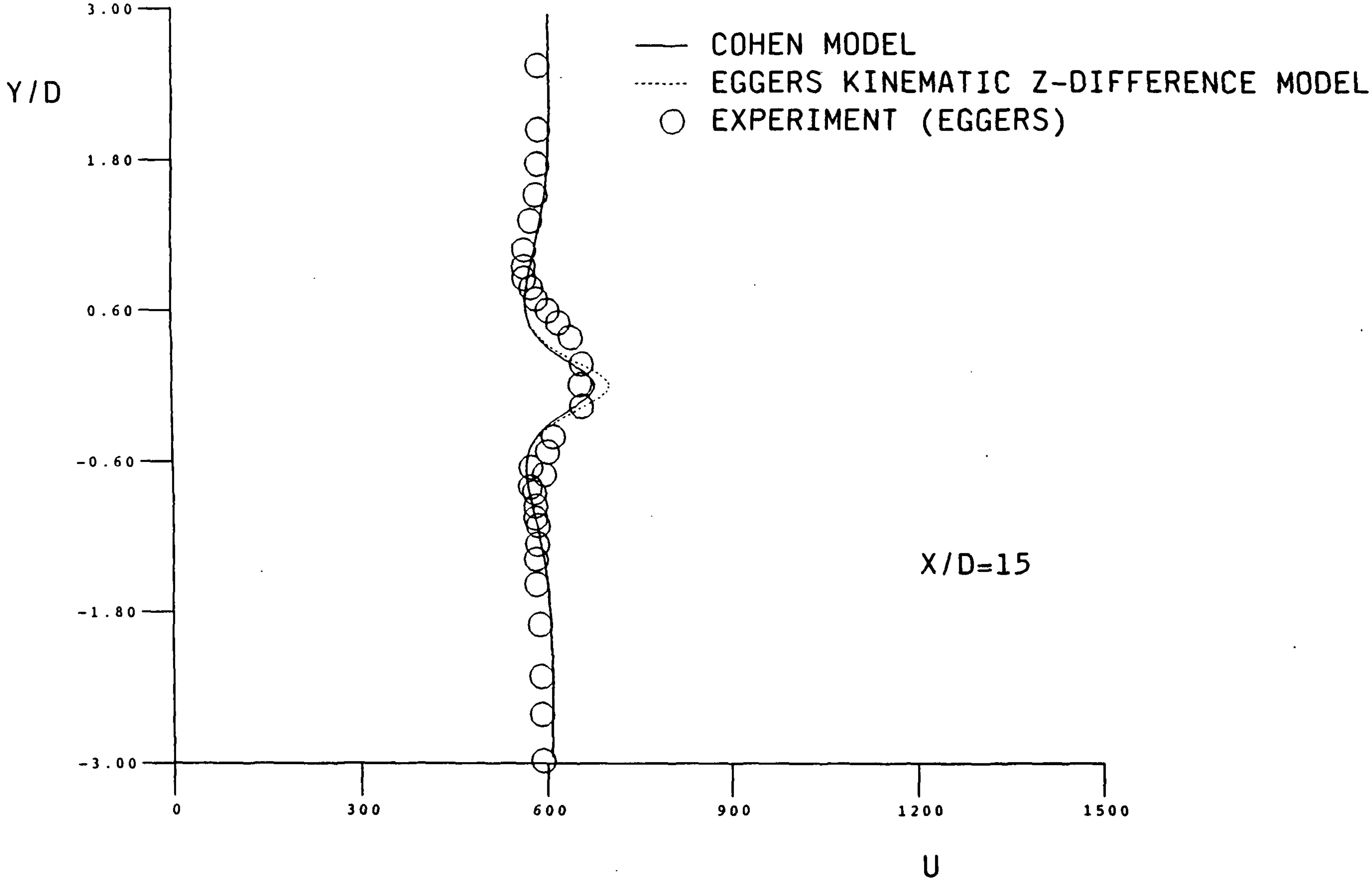

Fig. 11 Velocity Profile

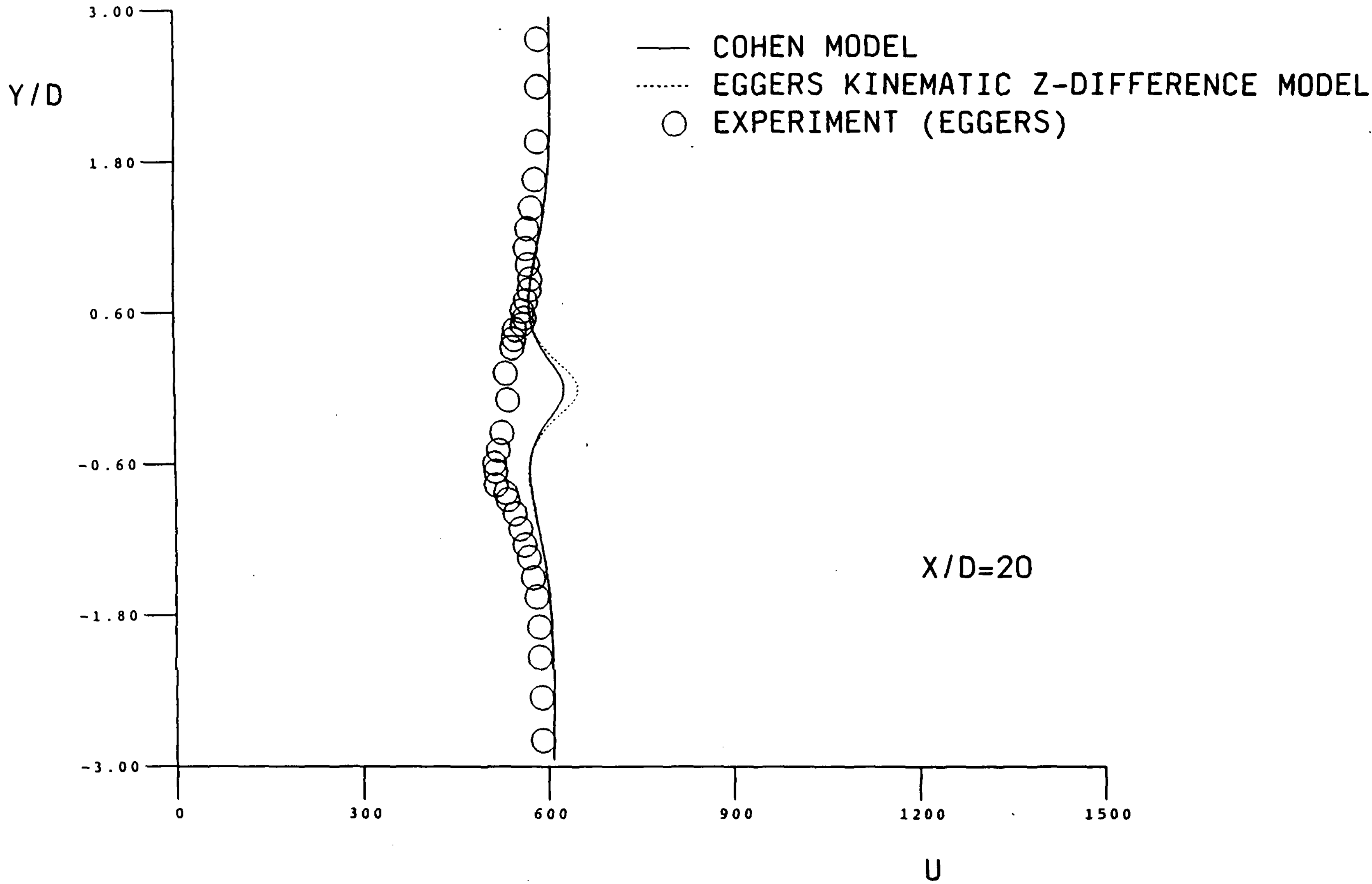

Fig. 12 Velocity Profile

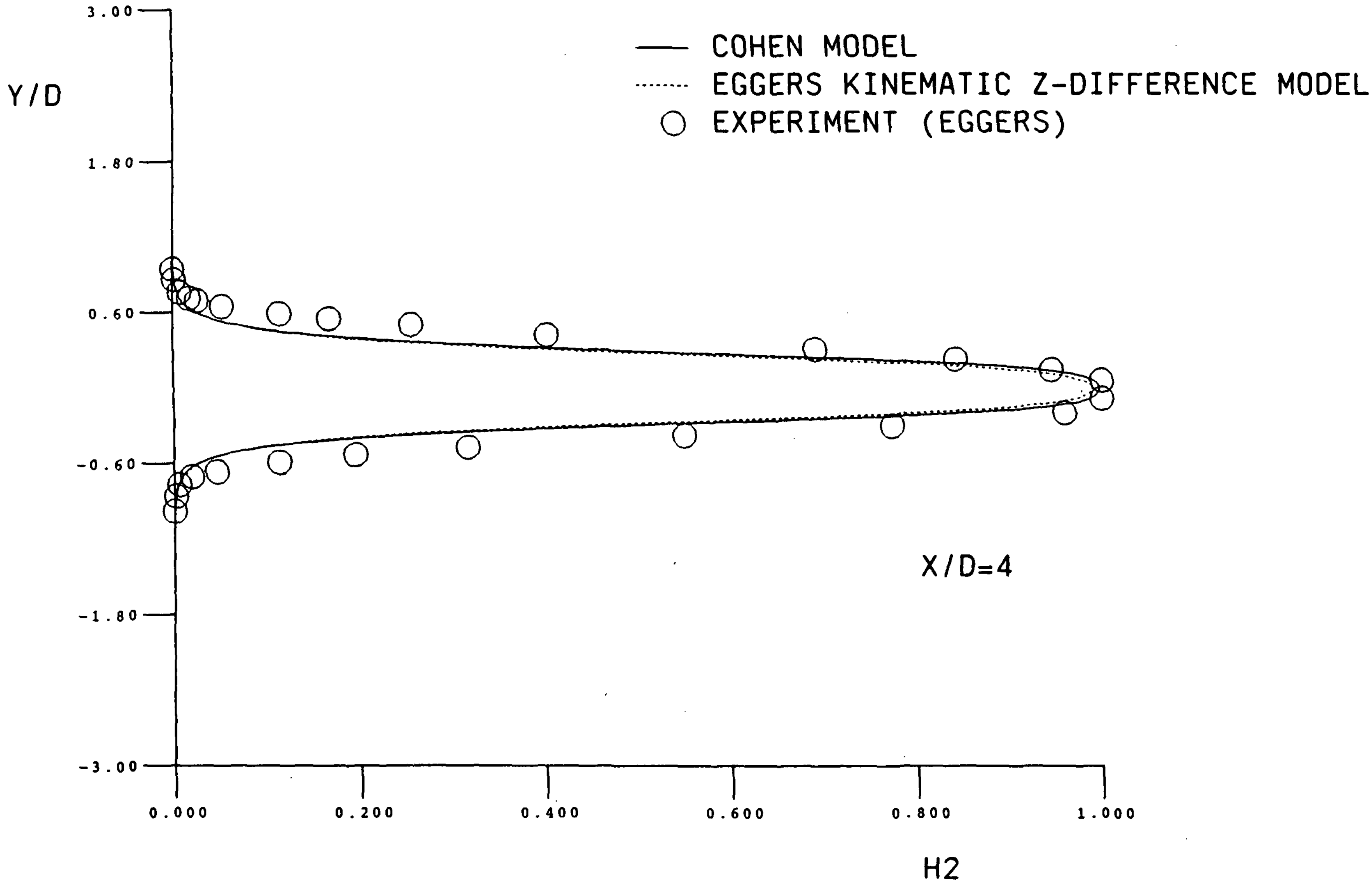

Fig. 13 Hydrogen Mass Fraction Profile

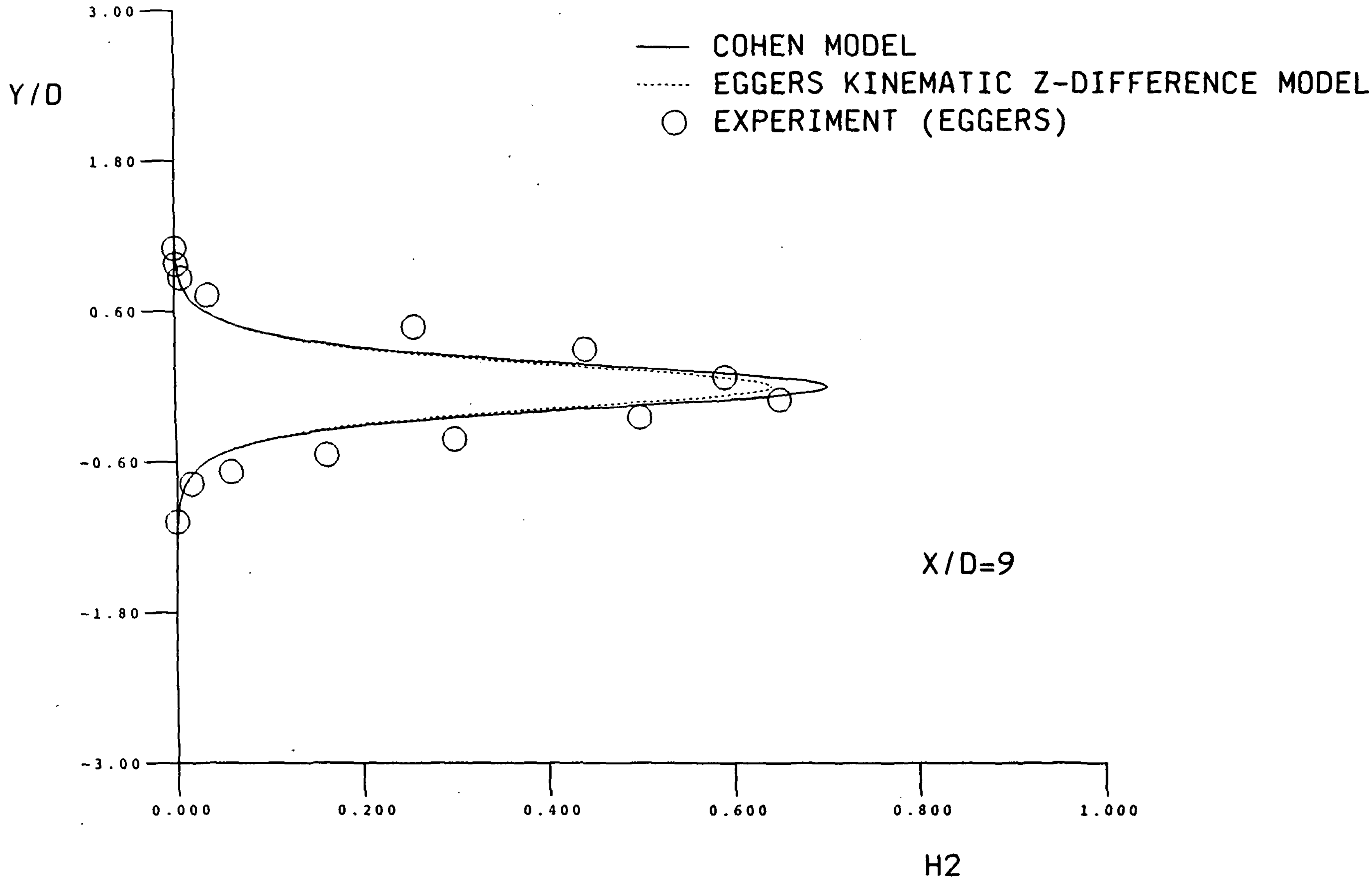

Fig. 14 Hydrogen Mass Fraction Profile

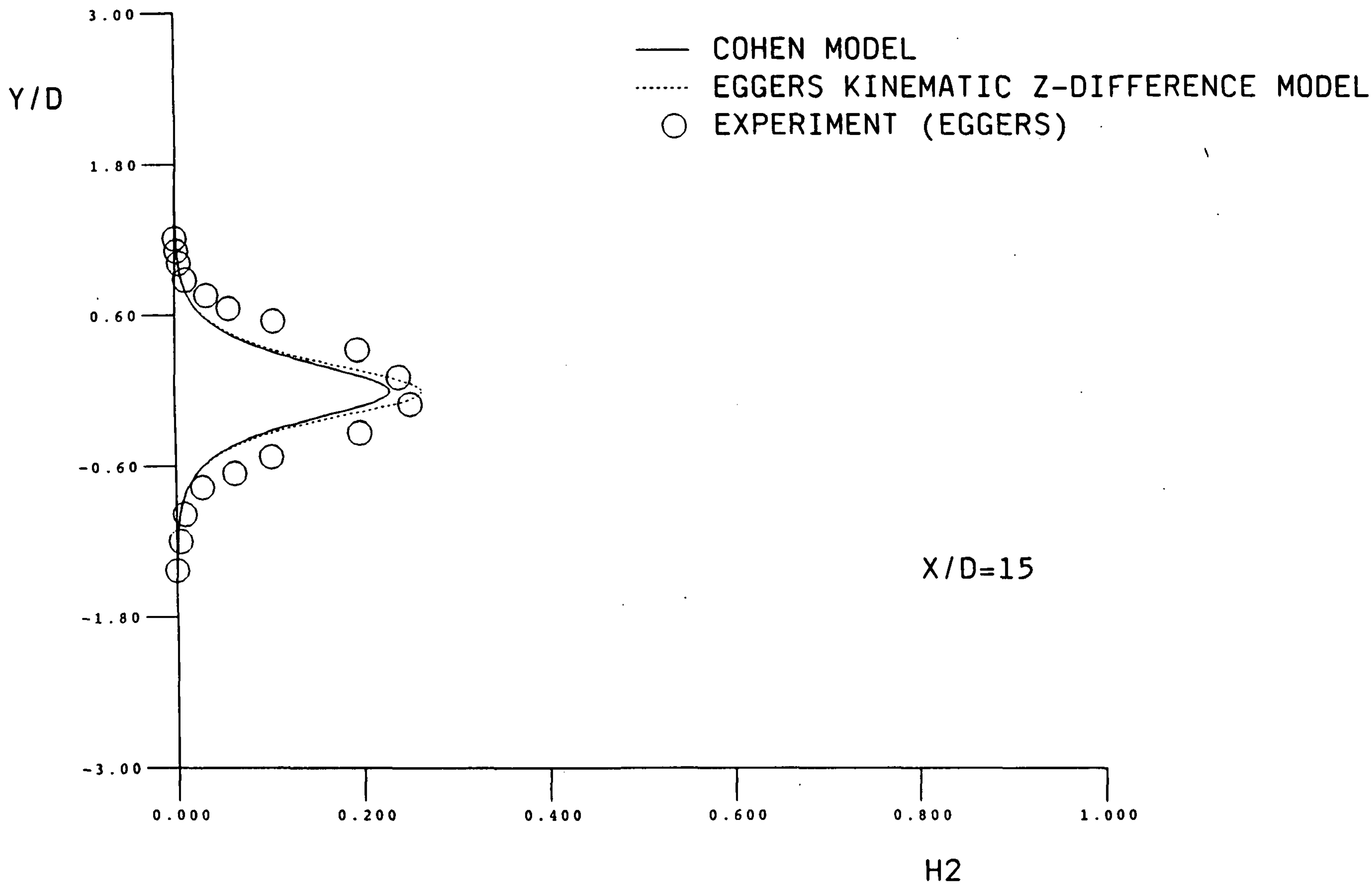

Fig. 15 Hydrogen Mass Fraction Profile

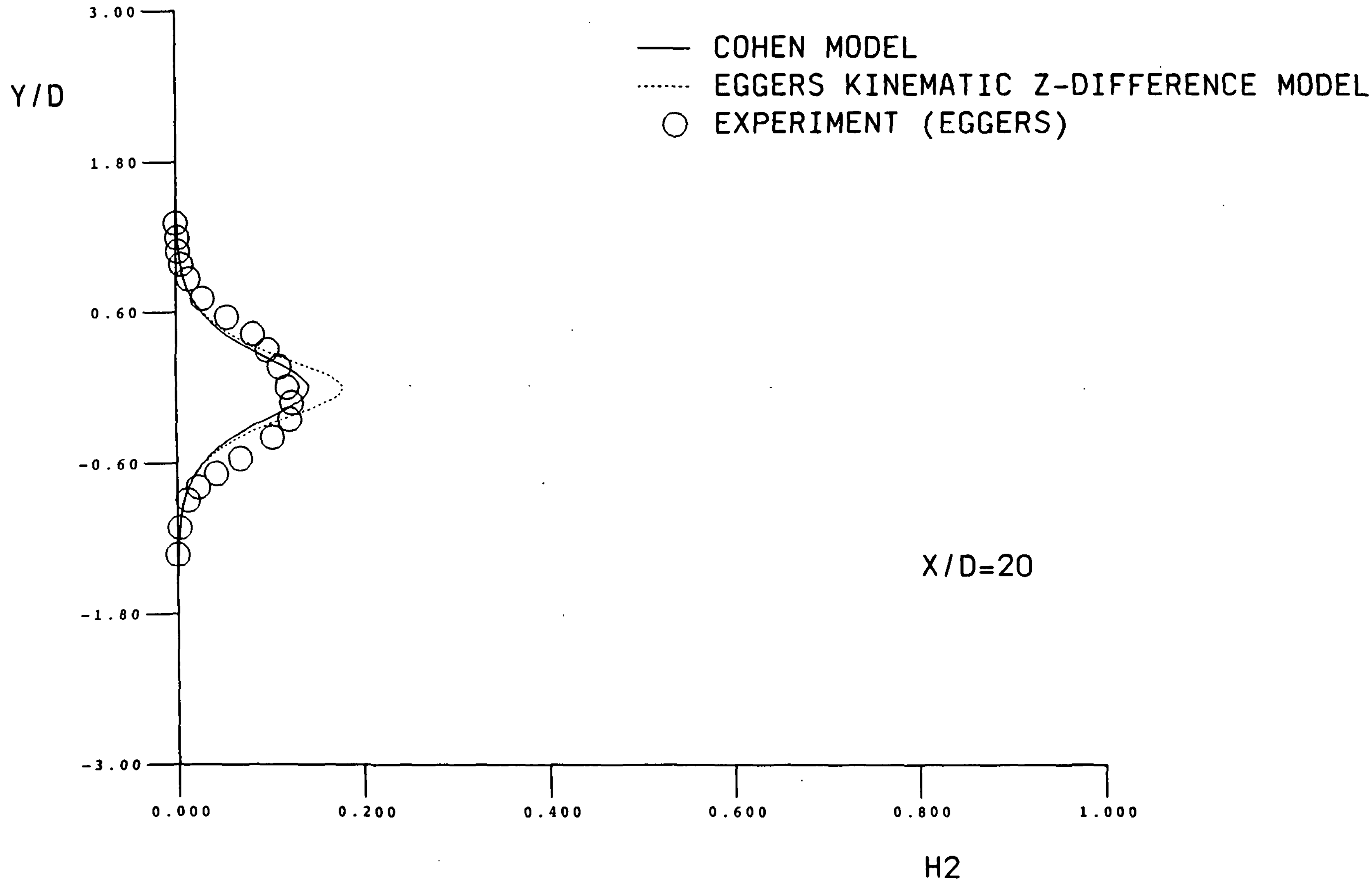

Fig. 16 Hydrogen Mass Fraction Profile

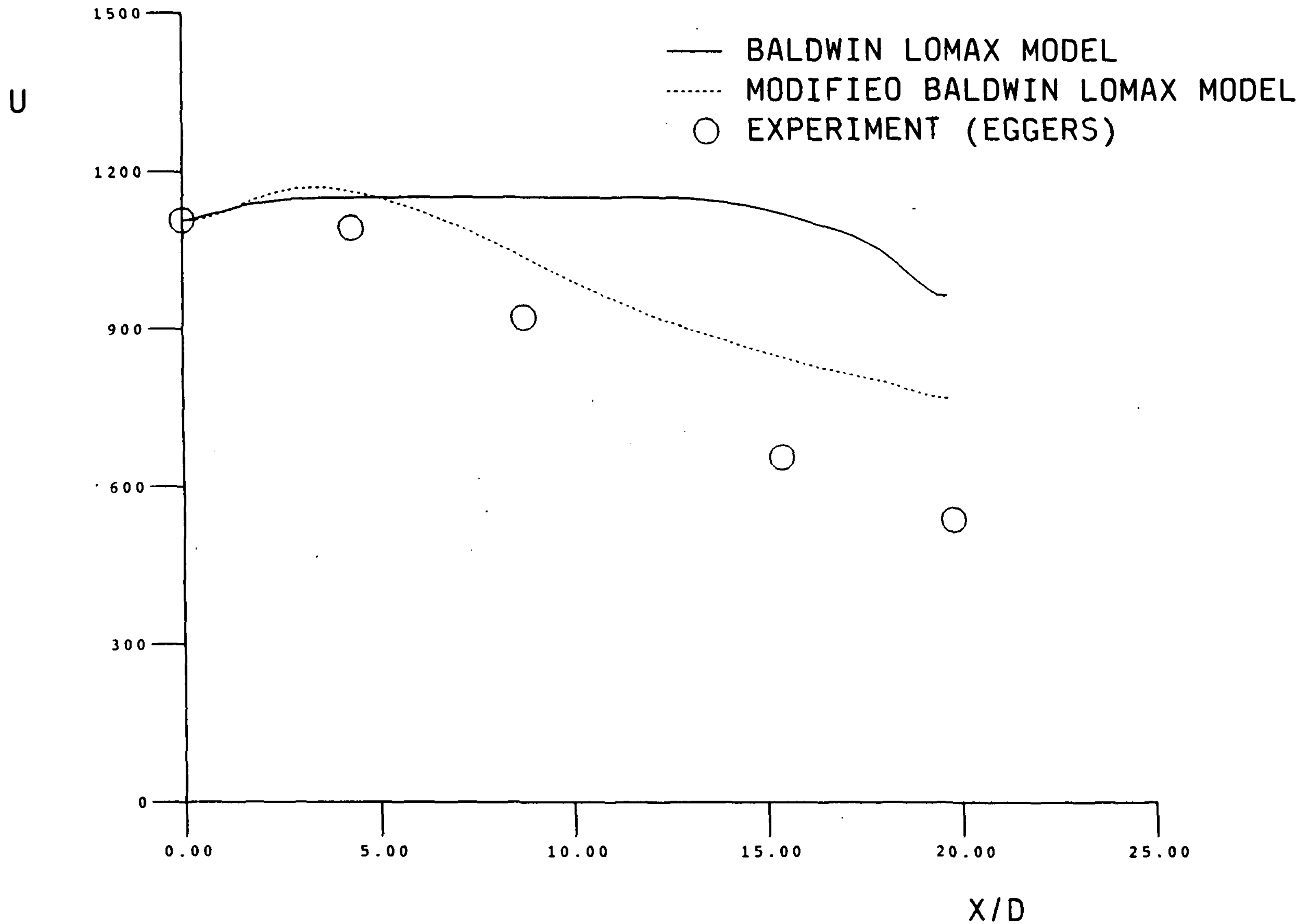

Fig. 17 Velocity Distribution Along the Centerline

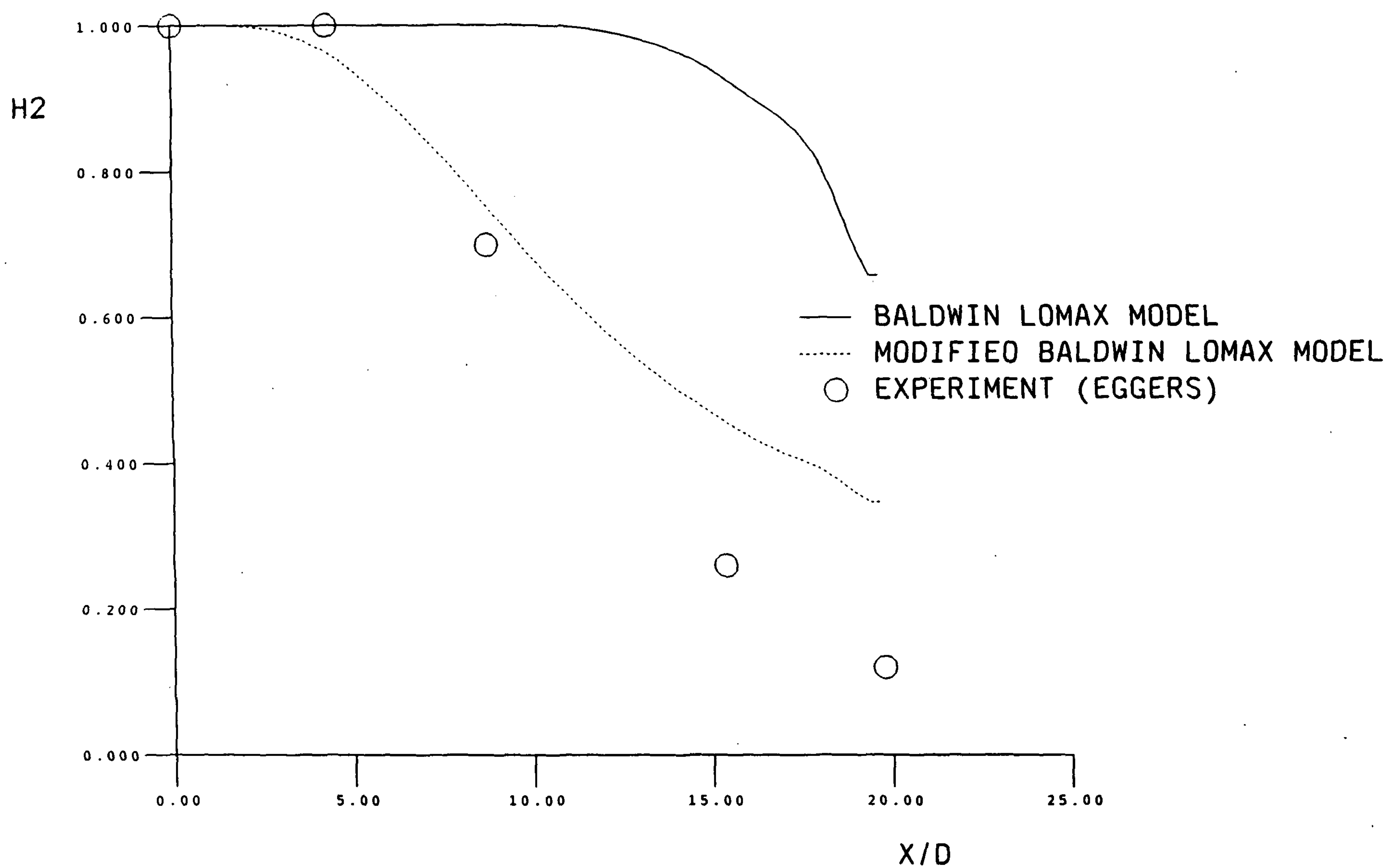

Fig. 18 Hydrogen Mass Fraction Distribution Along the Centerline